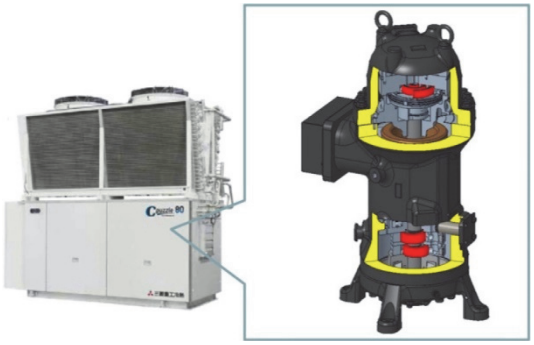
Large Capacity Two Stage Compressor for CO_2 Refrigerators Contribute to Global Environment



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Mitsubishi Heavy Industries Thermal Systems, Ltd. has developed a large-capacity two-stage refrigeration compressor which uses low-GWP CO_2 as the refrigerant. To increase capacity to 40 horsepower from the conventional 10, the compressor's basic structure was reviewed and a mechanism for intercooler, etc. were added. The rated compressor speed was decreased to reduce mechanical loss, achieving high efficiency. The lubricant oil viscosity was measured under actual operating conditions. Based on the results, oil passage inside the compressor and bearing clearance were optimized to ensure reliability. Consequently, the CO_2 compressor has large capacity, high efficiency and high reliability, and contributes to the reduction of global environmental load.

1. Introduction

In order to reduce global environmental load, heat pumps and refrigeration/air conditioning equipment are required to switch refrigerants to those with low global warming potential (hereinafter referred to as GWP). Using the natural refrigerant CO_2, two compression mechanisms (i.e. combined rotary and scroll) were effective in addressing the issues of large pressure difference and high operating pressure. Thus, Mitsubishi Heavy Industries Thermal Systems, Ltd. (hereinafter referred to as MTH) developed a 10-horsepower-class two-stage compressor combined rotary and scroll mechanisms (hereinafter referred to as "conventional compressor"), which is suitable for the operational characteristics of heat pumps and refrigeration/air conditioning equipment, and launched it on the market.

This conventional type of compressor is installed in MTH's commercial CO_2 condensing unit "C-puzzle" to achieve high efficiency, thereby satisfying the market demand for small and medium refrigeration capacities while reducing environmental load. Demand for the use of non-toxic and non-flammable CO_2 as the refrigerant in refrigeration systems in large freezer/refrigeration containers which commonly use ammonia is also increasing. Therefore, based on the conventional compressor, a new large-capacity two-stage compressor (hereinafter "developed compressor"), in which nominal output has considerably increased to 40 horsepower from the conventional 10, has been developed. Details regarding this development are presented in this report.

2. Outline of the developed compressor

2.1 Conventional compressor: structure and features

Structure of the conventional compressor, on which the developed compressor was based, is shown in **Figure 1**. The superior characteristics of CO_2 refrigerant include low GWP, non-flammability and non-toxicity. On the other hand, pressure difference between high and low pressure is several times larger than that of conventional HFC refrigerants, which may greatly affect compressor reliability. Increased risk of clearance leakage in the compression chamber which may lead to decreased efficiency is also of concern. In response, MTH's compressor adopts a two-stage compression structure with a compression mechanism at either end of the motor. As a result, pressure difference per stage is reduced, improving efficiency and reliability. As this structure allows

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intermediate pressure inside the shell, the shell wall can be thinner, resulting in reduction in size and weight. Moreover, an injection system is introduced between the first and second stages where pressure is intermediate, to improve both system performance and reliability in motor cooling.

We developed this two-stage compressor with a larger capacity, while retaining these features.

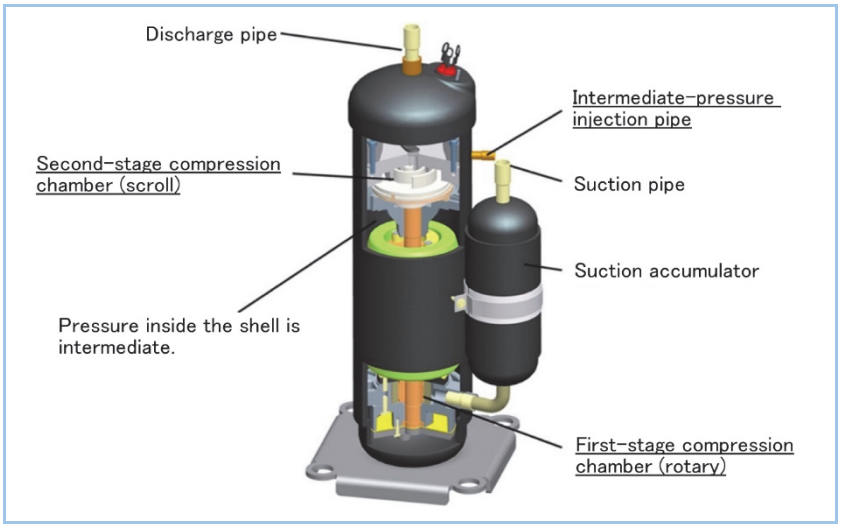

Figure 1 Structure of the conventional two-stage compressor

2.2 New large-capacity compressor: structure and features

Basic specifications of the newly-developed large-capacity model (hereinafter referred to as "large-capacity compressor") and the conventional compressor are compared in **Table 1**. With the same features as the conventional compressor, the new model has adopted a twin-rotary mechanism for the first stage compression, increasing capacity. A trochoid pump is used to supply oil to maintain sufficient oil pressure and flow rate, despite a longer oil passage due to the increased compressor capacity. Journal bearings, as in the case of the conventional compressor, are used to realize maintenance-free, long-life operation. Moreover, in order to improve the system COP, the displacement ratio between the first and second stages has been optimized under the freezing/refrigeration conditions (details are described in the following sections). The discharge path structure of the first-stage compression chamber was changed so the compressed refrigerant would be discharged into a pipe outside the chamber. As a result, an intercooling system could also be incorporated. When the refrigerant is compressed to an intermediate pressure level, its temperature increases as well. The intercooling system cools this hot refrigerant to the ambient air temperature. The cooled refrigerant with an increased density is then drawn into the second-stage compression chamber. Efficiency of the compressor thus improves.

Table 1 Basic specifications of the large-capacity compressor (in comparison with the conventional compressor)

		[Conventional compressor] 10-horsepower two-stage compressor	[Large-capacity compressor] 40-horsepower large-capacity two-stage compressor
Structure inside the compressor	First-stage compression chamber	Single rotary	Twin rotary
	Second-stage compression chamber	Scroll	Same as the conventional compressor
	Oil supply pump	Rotary pump	Trochoid pump
	Bearing	Journal bearing	Same as the conventional compressor
For COP improvement	Displacement ratio	Set to handle both hot water supply and freezing/refrigeration	Optimized for freezing/refrigeration
	Intercooling	No	Yes

The structure of the large-capacity compressor and the flow of the refrigerant gas during operation are shown in **Figure 2**.

When drawn through the suction inlet, the refrigerant gas (CO_2) is cooled by the intercooler outside the compressor after first-stage compression with a twin-rotary mechanism. The intercooled

refrigerant is then returned into the intermediate pressure shell, where the intermediate pressure refrigerant is also introduced from the injection port and combined, before being drawn into the second-stage scroll compression chamber. The compressed refrigerant gas is then discharged from the discharge outlet on the top of the compressor through the discharge port and sub-ports of the fixed scroll.

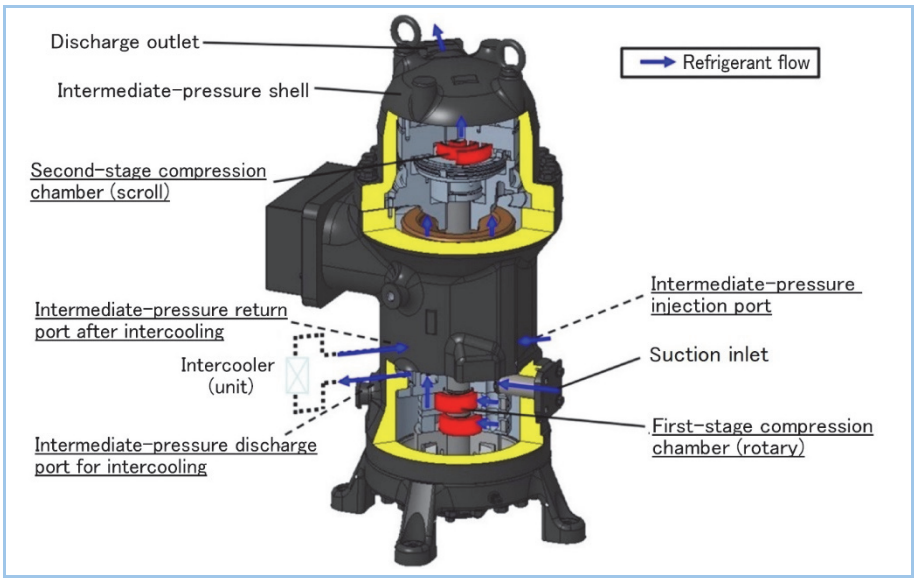

Figure 2 Large-capacity two-stage compressor structure and refrigerant flow

3. Issues accompanying an increase in capacity and their solutions

3.1 Performance

Nominal output of the large-capacity compressor is approximately four times that of the conventional compressor (Table 1). As capacity increases, a larger area of each bearing is subjected to sliding. Performance is expected to decrease due to greater mechanical loss from the bearings. Therefore, the compressor rated speed has been decreased to reduce such mechanical loss.

In a two-stage compressor, the first-stage displacement volume (V_1) contributes to the cooling capacity of the compressor. V_1 was set at the largest possible volume under the limitations imposed by the layout (compressor size). As cooling capacity is the product of V_1 and the compressor speed, the rated performance conditions under which the required cooling capacity can be met by the compressor were first determined. Compressor speed could be set approximately 25% lower than the conventional compressor under these conditions (**Figure 3**).

The ratio of the second-stage displacement (V_2) to first-stage displacement (V_1), referred to as V_2/V_1, affects COP under the given operating conditions (i.e. high or low pressure). Unit COP calculated and plotted against the parameter of V_2/V_1 under the refrigeration and freezing conditions is shown in **Figure 4**. Based on these results and in consideration of the intermediate pressure restrictions and other factors, optimal V_2/V_1 for a refrigerator is determined to be 0.7. From this, the second-stage displacement (V_2) was also determined. Moreover, using the same method as the conventional compressor, the size of each part was designed according to these displacements. Results of estimated losses under the rated conditions for both the conventional compressor and the large-capacity compressor are shown in **Figure 5**. These results confirm that the decreased rated speed of the large-capacity compressor reduces mechanical loss (sliding loss) as intended. A leakage loss reduction, which is the outcome of the optimized discharge ports (including sub-ports) and clearance values in the compression chambers, is also shown in the figure. With these reductions, compressor efficiency is expected to improve by approximately 4.0% over the conventional compressor, and this is confirmed by the measurement results of compressor efficiency under the rated conditions in **Figure 6**.

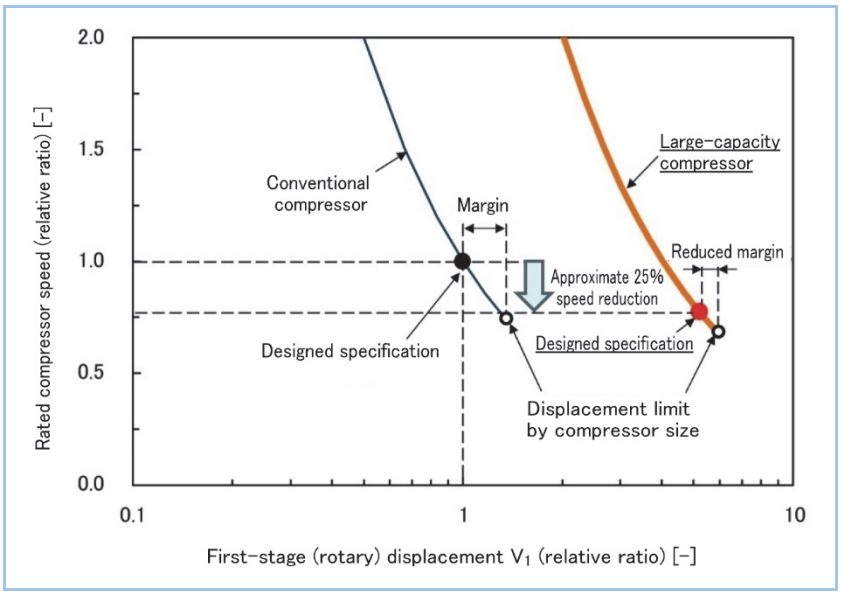

Figure 3 Correlation between first-stage displacement and rated compressor speed

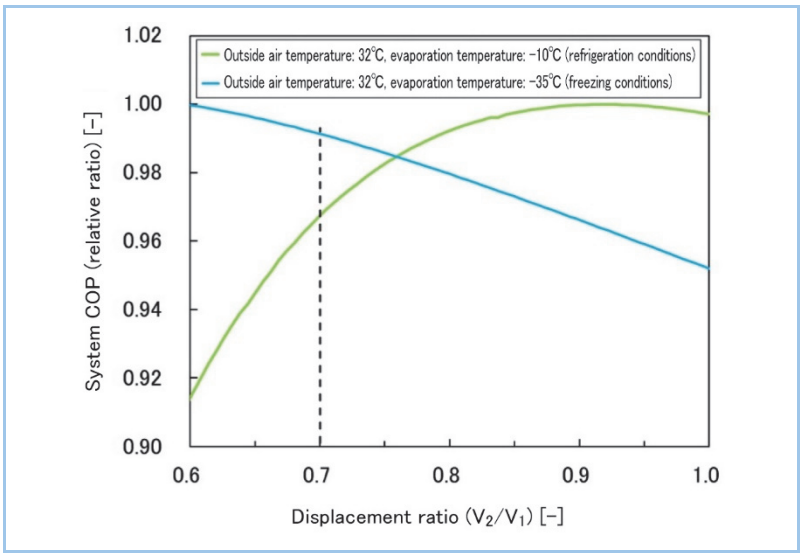

Figure 4 Relationship between displacement ratio and COP

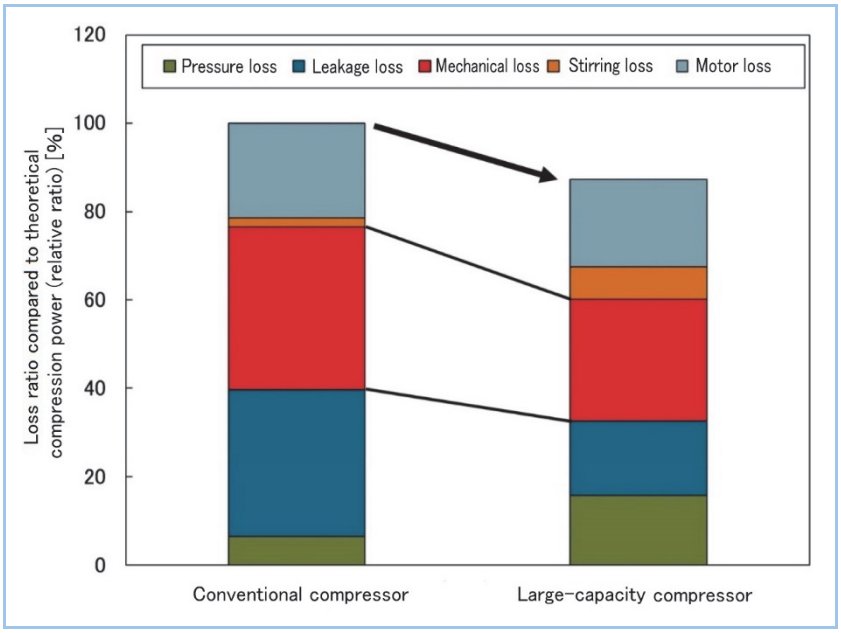

Figure 5 Percentages of different types of losses in the conventional compressor and the large-capacity compressor (estimated)

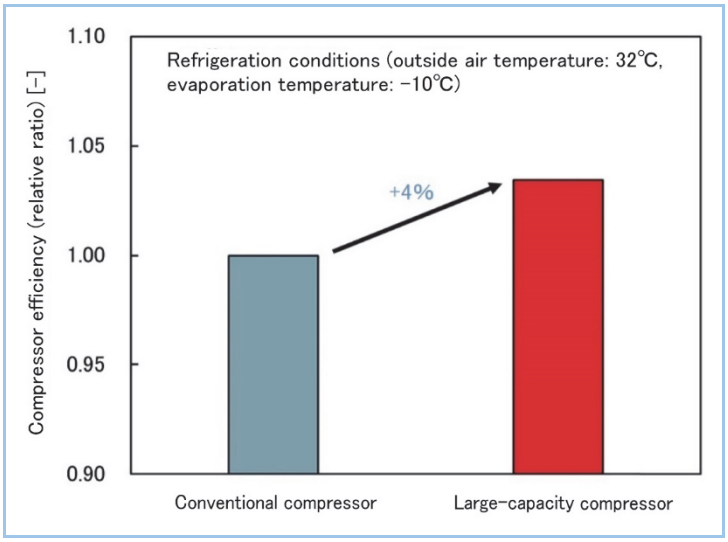

Figure 6 Comparison of compressor efficiency based on measurement values

3.2 Reliability

Regarding reliability, securing the required amount of oil for the increased capacity and ensuring oil film formation on the sliding surfaces are major challenges.

When loaded, the axis of rotation of the compressor bearing, which does not align with the center of the shaft, moves as the angle of rotation (phase) changes. To ensure reliability, an oil film of a certain minimum thickness is needed, even when the oil film is the thinnest among the changing positions of the axis of rotation (minimum oil film thickness).

Examples of the trajectory of the axis of rotation of the rotary bearing and minimum oil film thickness are shown in **Figure 7**. The trajectory of the rotation axis and the corresponding minimum oil film thickness are strongly affected by oil viscosity. Therefore, accurately estimating the viscosity of lubricant oil in the bearing when determining the bearing specifications is important. Parameters influencing viscosity are ambient pressure and temperature. In this large-capacity two-stage compressor, the inside of the shell containing the bearings is subjected to an intermediate pressure and may reach a supercritical state in some cases, for which available data on oil viscosity is scarce. Accurately predicting oil temperature is also difficult, due to factors such as the amount and temperature of intermediate-pressure injection refrigerant and heat transfer to the shell. In this development, in addition to pressure and temperature, measurement of refrigerant oil viscosity was performed, and the results were reflected in the bearing design. Thus, a compressor with high reliability could be designed, while continuing to use journal bearings as in the case of the conventional compressor.

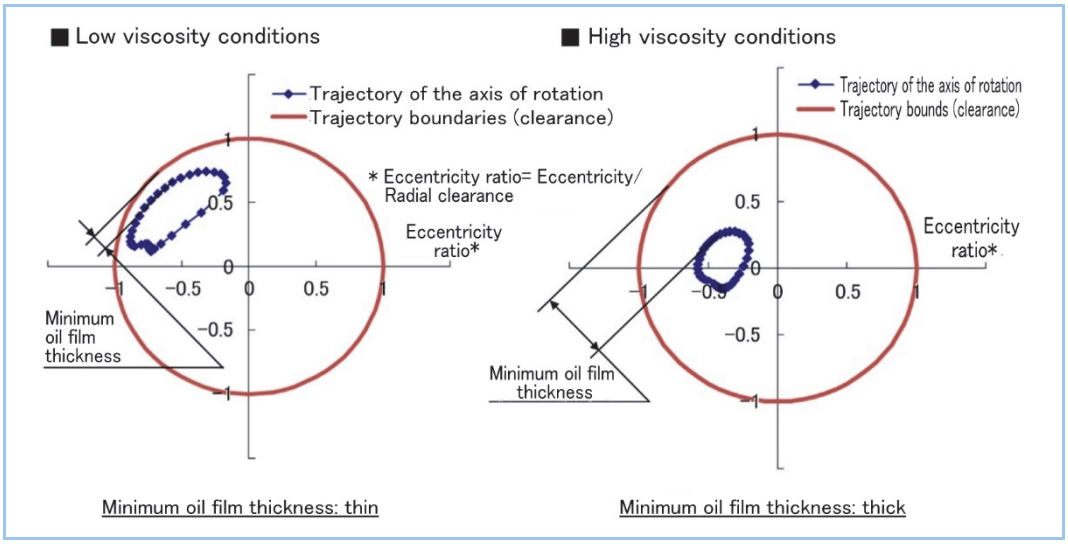

Figure 7 Trajectory of the axis of rotation of the rotary bearing and minimum oil film thickness

Measurement points for lubricant oil viscosity and temperature, along with the oil viscosity measurement values and the maker's catalog values, are shown in **Figure 8**. Viscosity and temperature were measured in the oil sump at the bottom of the compressor, using a piston viscosity sensor (viscosity measurement range of 0.5-10 cP). Viscosity of the oil was shown to reach a supercritical state at high temperatures, exceeding the catalog value, which confirms that the reliability of bearings could be sufficiently ensured.

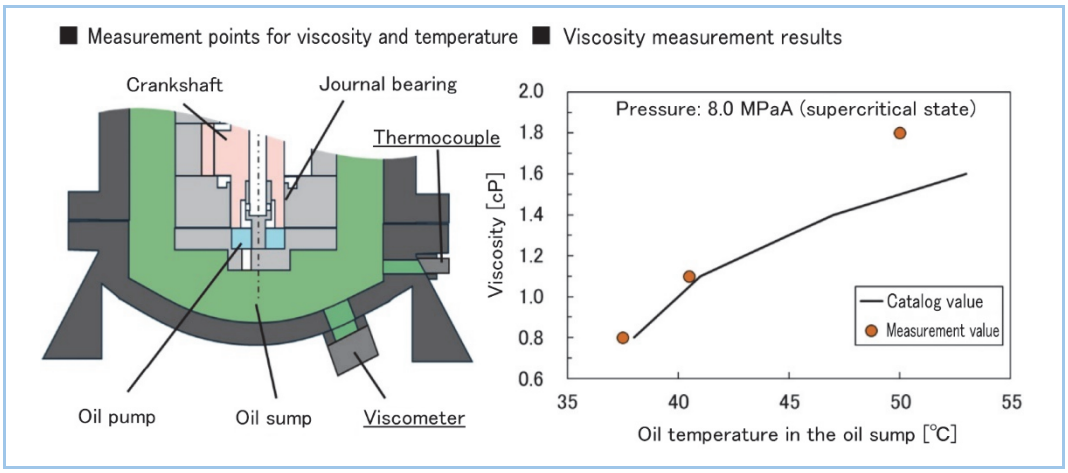

Figure 8 Schematic diagram of oil viscosity measurement and the measurement results

4. Conclusion

(1) A large-capacity CO_2 two-stage compressor, in which capacity (nominal output) was expanded to 40 horsepower from the conventional 10, was newly developed.

(2) By reviewing the basic specifications, the new two-stage compressor achieved increased capacity, while retaining the same features as the conventional compressor.

(3) Mechanical loss could be reduced by maximizing displacement and decreasing rotation speed, which improved compressor efficiency by 4.0% from the conventional compressor.

(4) Since available data on viscosity of supercritical lubricant oil is scarce, lubricant oil viscosity was measured and the results were used in bearing design, resulting in a compressor with high reliability.

(5) The 40-horsepower large-capacity two-stage compressor reported herein is incorporated in "C-puzzle80", a CO_2 condensing unit developed by Mitsubishi Heavy Industries Air-conditioning and Refrigeration Corporation, and contributes to a reduction in global environmental load.